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[ADP No. 07806326001]

Incorporated in the United Kingdom

United Kingdom  
IX 8AQ  
LONDON  
One Bruton Street  
MARCONI CASWELL LTD

Incorporated in the United Kingdom

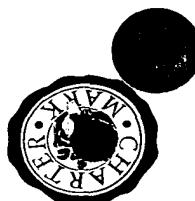
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INTENSITY-WAVELENGTH CODED FIBRE BRAGG GRATINGS SENSORS

4. Title of the invention

If the applicant is a corporate body, give the country/state of its incorporation

1. Your reference	P/61761.GBA
2. Patent application number	9906361.2
(The Patent Office will fill in this part)	
3. Full name, address and postcode of the or of	19 MAR 1999
Macrom Electronic Systems Ltd	
4. The Grove	Warren Lane
5. each applicant (underline all surnames)	each applicant (underline all surnames)
6. SECTION 30 (SEARCH) APPLICATION FORM	19 MAR 1999
7. Middx HA7 7LT	19 MAR 1999

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Ian Collier 01245 275125

CF HOSTE  
19<sup>th</sup> March 1999

Signature: *John C. F. Hoste*  
Application: *C. F. Hoste*

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11. We request the grant of a patent on the basis of this application.

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## Request for preliminary examination and search (Patents Form 9/77)

**to grant of a patent (Patients Form 177)**

## Statement of Inventionship and Right

## Translations of Priority documents

## Priority documents

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### Drawing(s)

## Abstract

### Claim(s)

## Description

## Continuation sheets of this form

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9. Enter the number of sheets for any of the

20 require a very large number of electrical connections, making them cumbersome and prone to electrical failure.

15 case in structural monitoring of structures such as bridges and buildings, such sensors that when it is required to measure strain at a large number of points, as would be the developed across it. A particular disadvantage of such electrical resistance sensors is current to the device and the other two for accurately sensing the potential difference compared four terminal devices in which two terminals were used to apply electrical strain sensors relied on a change in electrical resistance with strain and typically To measure strain within such structures it is known to use a strain sensor. Early

10 other structures as well as in their engineering design.

5 Structural health and load monitoring of structures such as bridges and buildings is integrity of structures such as aircraft, space platforms, marine vessels, bridges and can be used in assessing damage and warning of impending weakness in the structural original length, which is indicative of the loading of the structure. Such information the structure, that is the change of length (extension or contraction) relative to the well known. Typically such systems measure the tensile or compressive strain within

healh and load monitoring.

1 This invention relates to strain sensing and more especially to a strain sensor, apparatus for use with and a method of operating a strain sensor for sensing structural

## STRAIN SENSING

to measure strain at a number of different points along the optical fibre.

fibre, each of which reflects light at a different characteristic wavelength, it is possible

wavelength of each grating. By providing a number of gratings along the length of the

optical fibre is measured by measuring a change in the characteristic

of the grating. Strain is subjected to tensile or compressional strain which affects the pitch

determined by the pitch of the grating. This characteristic wavelength will change if

respective strain sensor, reflects light at a characteristic wavelength which is

often termed fibre Bragg gratings, each Bragg grating which itself constitutes a

Fabry-Pérot resonators or intra-core Bragg gratings. In the case of the latter which are

applied strain. Such components can comprise birefringent elements, micro-bends,

comprise an optical fibre containing a number of components which are responsive to

number of the problems of electrical resistance sensors. Optical fibre strain sensors

More recently optical fibre strain sensors have been proposed which overcome a

Whilst optical fibre strain sensing is found to be effective the inventors have appreciated that it suffers from certain limitations. Fibre Bragg gratings addressed in the wavelength, time and space domains. The number of fibre Bragg multiplexing is limited which is a consequence of the limited spectral range of the currently available optical sources is 30 to 40 nm and it is usually required to be able to measure strains in the region of 3,000 to 5000  $\mu\epsilon$  (that is a 0.3% - 0.5% mechanical extension/contraction) which corresponds to a change in the characteristic wavelength of each sensor to ensure that at its maximum wavelength change the wavelength range to each sensor is well defined gratings sensors within a single optical fibre it is necessary to dedicate a well defined range of the sensor in the adjacent wavelength band since, under these conditions, it is impossible to discriminate between light reflected from the two sensors. As a result the number of gratings that can be incorporated in a single fibre is limited. The present invention has arisen in an endeavour to overcome at least in part the limitations of the known strain sensing arrangements.

the internal strain of the structure and/or any load to which it is subjected. structurally integrate optical fibre sensors thereby enabling continual monitoring of their compatibility has led to the emergence of so-called "smart structures" which

By securing the regions of the optical waveguide which include the reflecting structures, to an object, any change in length of the object will cause a change in the length of the reflecting structure which will be detected as a change in characteristic wavelength. Furthermore, if these regions of the optical waveguide are placed in thermal contact with an object, any change in temperature will cause a change in the physical length of the reflecting structure which will be detected as a change in characteristic wavelength and the strain sensor of the present invention thus acts as an effective temperature sensor. It will be appreciated that in both measuring strain and temperature the strain sensor measures a change in the length of at least a part of the reflecting structure, that is it measures an internal strain of the sensor. In 15 20

According to the present invention a strain sensor comprises an optical waveguide having a plurality of reflecting structures along its length, wherein each structure reflects light at a different characteristic wavelength which changes in dependence on a change of physical length of at least part of the reflecting structure; characterised in that the reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them. Since discrimination between the reflection characteristics of structures which are adjacent in wavelength is based on the relative magnitude of their reflectivities, this allows reflecting structures to have overlapping wavelength bands thereby enabling more reflecting structures to be incorporated within an optical waveguide for a given optical spectral range.

20 determines the pitch and hence the characteristic wavelength of the grating and the projection. In such a case the spacing of the fringes of the holographic projection fibre core by, for example, exposing the fibre to ultra-violet (UV) holographic with germanium oxide, and the or each grating structure is optically written into the includes a photo refractive dopant, such as for example a silica optical fibre doped change in the pitch of the grating. In a preferred implementation the optical fibre grating, in which a change in the characteristic wavelength is in consequence of a or each reflecting structure comprises a grating structure, most preferably a Bragg 15 Most conveniently the optical waveguide comprises an optical fibre and preferably the

10 therefore discrimination between the reflecting structures is possible. least one of the pair of characteristic wavelengths always remains resolvable and the adjacent wavelength. Such an arrangement is particularly advantageous since at by at least the width of the reflection characteristic of the structure which reflects at least the wavelength is configured such that the two wavelengths are separated characteristic wavelengths is configured such that the two characteristic wavelengths. Preferably the reflecting structure which reflects light at two the structure adjacent in wavelength is selected to reflect light at two characteristic configured such that one structure reflects light at one characteristic wavelength and advantageously the reflecting structures which reflect at adjacent wavelengths are 5

a sensor which is for measuring strain in an object to which it is attached. broadly as a sensor which relies on a change in length and should not be restricted to the context of the present invention the term strain sensor is intended to be construed

discriminate between reflecting structures which are adjacent in wavelength. relative magnitude of the intensity at which light transmission is attenuated to means for utilising the relative magnitude of the intensity of the reflected light or the means for utilising the relative magnitude of the intensity of the reflected light further comprises

20

changes in wavelength at which light transmission is attenuated. measures light transmitted by the sensor and determines the changes by measuring the attenuation of transmitted light. In an alternative arrangement the detector means at the far end of the waveguide the changes in wavelength will appear as a change in reflected will pass along the optical waveguide substantially unattenuated. As a result, only reflects light at various characteristic wavelengths, any light which is not measuring the wavelengths at which the sensor reflects light. Since the strain sensor preferably the detector means determines the changes in characteristic wavelength by

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of at least a part of the respective reflecting structure. reflecting structure reflects light, said changes being indicative of a change in length means for determining the change of characteristic wavelength at which each the range of wavelengths over which the reflecting structures reflect and detector waveguide of the sensor, said light having a wavelength range which covers at least comprises a strain sensor described above; a light source operable to apply light to the according to a second aspect of the invention an apparatus for measuring strain intensity of the UV light determines the reflectivity at the characteristic wavelength.

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intensity of the UV light determines the reflectivity at the characteristic wavelength.

9

P/61761.GBA/PC

structures in thermal contact with the object such that a change in the temperature of comprises placing a part of the waveguide having at least a part of one of the reflecting when it is desired to measure the temperature of an object, the method further 20 a change in the physical length of the reflecting structure. Alternatively, or in addition, structures to the object such that a change in the physical length of the object causes securing a part of the waveguide having at least a part of one of the reflecting secures to the object strain within an object the method further comprises When it is desired to measure strain

15 adjacent in wavelength.

transmitted light is attenuated to discriminate between reflecting structures which are intensity of reflected light or the relative magnitude of the intensity at which preferably the method further comprises detecting the relative magnitude of the

10 the wavelengths at which the transmission of light through the sensor is attenuated. Alternatively the changes in characteristic wavelength can be detected by measuring

wavelengths at which the sensor reflects light.

5 Preferably the changes in characteristic wavelength are detected by measuring the change in the characteristic wavelength at which the reflecting structures reflect light. wavelength over which the reflecting structure reflects light, and detecting any of the sensor, said light having a wavelength range which covers at least the range of comprises providing a strain sensor described above, applying light to the waveguide according to yet a further aspect of the invention a method of measuring strain

In order that the invention may be better understood a strain sensor and apparatus in accordance with the invention for measuring strain and/or temperature sensitive apparatus in accordance with the invention for the apparatus of Figure 1; Figure 2(a) is a series of plots of measured reflectivity  $I$  versus wavelength for different applied strains for the apparatus of Figure 1; Figure 2(b) is a plot of the measured wavelength shift  $\Delta\lambda$  of the peak (x) of Figure 2(a) versus strain;

Figure 3(a) is a series of plots of measured reflectivity  $I$  versus wavelength for a further strain sensor for different applied strains; and Figure 3(b) is a plot of the measured wavelength shift  $\Delta\lambda$  for the two peaks (x,y) of Figure 3(a) versus strain.

the object causes a change in the physical length of at least a part of the reflecting structure.

P/61761.GBA/PC

respectively which will hereinafter be referred to as "low" and "high" reflectivity.  $\lambda_{u+1}$  in Figure 1 are arranged to alternately have reflectivities of 50 and 95% The gratings which reflect at adjacent wavelengths, for example  $\lambda_1$  and  $\lambda_2$  or  $\lambda_1$  and

20

thereto.

Number 1, 1998, paragraph 2.3, which is hereby incorporated by way of reference an article by one of the inventors in the GEC Journal of Technology Volume 15 fibre gratings using holographic projection is known and is for example described in

15 determined by the pitch of the respective grating. The method of producing optical selected to have a characteristic wavelength, denoted  $\lambda_1$  to  $\lambda_{u+1}$  in Figure 1, which is to an appropriate pattern of UV light. Each grating structure within the fibre is hence a Bragg diffraction grating can be defined within the core by exposing the core which when exposed to UV light results in a permanent change of refractive index and

10 or point by point writing can be used. Germanium oxide is a photo refractive dopant (UV) light using holographic exposure, though other techniques such as a phase mask within the core of the optical fibre by exposing the core of the fibre to ultra-violet of the optical fibre a plurality of Bragg diffraction gratings. Each grating is produced

5 oxide. Spaced along the length of the optical fibre there are provided within the core inventive in its own right, comprises a silica optical fibre which is doped germanium fibre strain sensor 6, which is a key aspect of the present invention and considered photodiodes 10 and 12 respectively, a mixer circuit 14 and a processor 16. The optical

2, a tunable filter 4, an optical fibre strain sensor 6, a directional coupler 8, two referring to Figure 1 a strain sensing apparatus comprises a broad band light source

to the first input of the directional coupler 8 which splits the light such that half passes domain such as for example a tuneable laser diode. The swept light output is applied can be replaced with a suitable optical source which is tuneable in the wavelength band source 2. In an alternative arrangement the light source 2 and tuneable filter 4 produces an optical output which is swept over the range of wavelengths of the broad acousto-optic tuneable filter or a scanned Fabry-Pérot filter, such that the filter applied to the wavelength selective filter 4, which can comprise for example an output over the wavelength range  $1550 \text{ nm} \pm 30 \text{ nm}$ . This continuous light output is or Erbium doped fibre amplifier, is operable to produce a continuous broad band light The broad band light source 2, which conveniently comprises a light emitting diode 20

fiber is connected either by adhesive or by mechanical clamping. Flanges or mounting brackets made of metal, glass or a plastics material, to which the measured. Such mechanical securing means can comprise an encapsulating tube, means to enable the fibre to be mechanically secured to an object whose strain is to be sensor 6 further comprises associated with each grating region mechanical securing discrimination between light reflected from the respective gratings. The optical fibre adjacent in wavelength have sufficiently different reflectivities to enable only. The important criterion is that the relative reflectivity of gratings which are adjacent in wavelength is not critical and the use of 50 and 95% are exemplary within the fibre. As will become apparent the absolute reflectivity of gratings which altering the intensity of the UV light used to expose and so define the grating structure Using the fabrication technique described this difference in reflectivity is achieved by 15

grating. These test data are for a sensor having an array of Bragg gratings having a wavelength for increasing amounts of applied tensile strain to the "low" reflectivity "low" and "high" reflectivity gratings which are adjacent in wavelength versus

20 Referring to Figure 2(a) there are shown the reflection intensity profiles for a pair of

spectral range.

since the source 2 is unlikely to produce a uniform light intensity output over its full preferable, though not essential, to normalise the reflection spectrum as described

15 is detected by the processor 16 which preferably comprises a spectrum analyser. It is

sensor 6 which has been normalised relative to the light applied to it and this spectrum

light source 2 the output from the mixer 14 represents the reflection spectrum of the

at that wavelength. As the tunable filter 4 scans over the wavelength bandwidth of the

sensor 6 at a given wavelength relative to the intensity of light applied to the sensor

10 circuit 14 such that the output represents the ratio of reflected light from the optical

The outputs from the respective photodiodes 10 and 12 are applied to the mixing

of the optical fibre.

along the length of the optical fibre and is dissipated in a light dump 18 at the far end

5 selective filter 4. The light which is not reflected by the optical fibre sensor 6 passes

passes to the second photodiode 12 and the remaining half towards the wavelength

sensor 6 travels back toward the directional coupler 8 where it is split such that half

photodiode 10. Light which is reflected by the Bragg gratings in the optical fibre

into and along the optical fibre sensor 6 and the other half passes to the first

9 P/61761.GBA/PC

number of gratings within a given spectral range. This band, whose width is approximately 500  $\mu$ e, it is still possible to double the they spectrally overlap, as illustrated in the middle profile of Figure 2(a). In spite of peaks from the "low" and "high" reflectivity gratings cannot be discriminated because measured; this is denoted by arrows "AA" in the Figure. In this band the reflection is a linear function of applied strain and includes a band over which strain cannot be applied tensile strain. As will be seen from this Figure, the change in wavelength  $\Delta\lambda$  Figure 2(b) is a plot of the wavelength shift  $\Delta\lambda$  of the reflectivity peak x versus

peak remains constant.

"high" reflectivity grating and hence the characteristic wavelength of its reflectivity grating. For clarity, it should be noted that in this example no strain is applied to the to increase and the peak moves toward and through the peak of the "high" reflectivity grating spacing, which causes the characteristic wavelength of the reflectivity peak x grating is applied to the "low" reflectivity grating, this causes an increase in the tensile strain is applied to the "low" reflectivity grating reflects light at a lower applied, it will be seen that the "low" reflectivity grating reflects light at a lower strain with the uppermost profile, which shows the sensor when no tensile strain is

wavelength.

strained in steps of 80  $\mu$ e up to 4000  $\mu$ e, which corresponds to a 4 nm change in reflectivity grating was kept strain free whilst the "low" (50%) reflectivity grating was 2 nm spectral spacing and a typical grating bandwidth of  $\approx$  0.4 nm. The "high" (95%)

Referring to Figure 3, this shows for such a sensor (a) a series of plots of measured

bandwidth of the high reflectivity grating.

spacing of the two characteristic wavelengths is selected to be at least as large as the 20 which is still of "low" reflectivity but reflects at two characteristic wavelengths. The sensor according to the invention to replace the "low" reflectivity grating with one the need to use ultra-narrow spectral response gratings, it is proposed in a further to noise ratio in the system. To minimise the effect of the overlapping region without 15 narrow spectral response gratings will reflect less light, which will degrade the signal and this band can be minimised by using narrow spectral response gratings. However, As described above, there is a band AA in which the two gratings spectrally overlap 15

doubled.

of gratings that can be incorporated within the fibre for a given spectral range is thus 10 the strain sensing spectral bandwidth for each grating is still  $\Delta\lambda_{BG}$ . The total number spectral spacing necessary between adjacent gratings is approximately halved, though discrimination of the light reflected from the respective gratings. As a result in the invention additionally encodes the reflectivity of adjacent gratings which enables 5 not cross each other. In contrast to the known sensors, the sensor of the present bandwidth  $\Delta\lambda_{BG}$  is necessary to ensure that reflection peaks for adjacent gratings do source and  $\Delta\lambda_{BG}$  is the spectral bandwidth of each fibre Bragg grating. The spectral fibre is determined by  $n \approx \Delta\lambda_{SR}/\Delta\lambda_{BG}$  where  $\Delta\lambda_{SR}$  is the spectral range of the light 20 In the known systems the number of gratings ( $n$ ) that can be incorporated into a single

reflectivity I versus wavelength for different applied strains to the "low" reflectivity gratings and (b) a plot of the measured wavelength shift  $\Delta\lambda$  for the reflection peaks  $x, y$  seen that as the "low" reflectivity grating is subjected to strain the pair of reflectivity peaks ( $x, y$ ) both shift at the same rate such that even when the spectral responses of the two gratings overlap at least one of the pair of peaks is always resolvable. Figure 3(b) shows the wavelength shift for both peaks ( $x, y$ ) for the dual peak response as AA over which strain cannot be measured is substantially reduced. The remaining information concerning both peaks of the dual peak response is considered the band crosses and circles, respectively, versus applied strain. It will be seen that when AA over which strain cannot be measured is substantially reduced if the spacing of the dual small band is due to the relatively broad bandwidth of the high reflectivity grating. Further tests have shown that the gap is virtually eliminated if the spacing of the dual peaks is increased or if the bandwidth of the high reflectivity peak can be reduced.

It will be appreciated that the present invention is not restricted to the specific embodiment described and that variations can be made which are within the scope of the invention. For example, in the apparatus described the intensity of the light reflected from the sensor is measured. In other embodiments it is envisaged to measure the light transmitted by the optical fibre, since the absorption loss in the fibre is negligible. Consequently, the sum of transmitted light and reflected light is measured from the sensor is measured. In other embodiments it is envisaged to reflect the light transmitted by the optical fibre, since the absorption loss in the fibre substantially unity and the change in characteristic wavelength of the Bragg gratings can be determined by measuring the change in wavelength at which the fibre attenuates transmitted light. It will be further appreciated that the invention is not 20

10 The operation of the strain sensor has been described by way of example to strain sensing within an object. It will be appreciated that the said strain sensor and apparatus can also be used to measure temperature, since a change in temperature of the grating will cause an expansion or contraction of the grating and so change the grating pitch. In such an application the optical fibre is placed in thermal contact, with the object rather than being secured to it.

## 5

Forms of optical waveguide could be used though they are likely to be less convenient of the structure. Although the sensor is conveniently formed as an optical fibre other provided their characteristic wavelength is affected by a change in the physical length limited to Bragg gratings, and other forms of reflecting structures can be used

1. A strain sensor comprising: an optical waveguide having a plurality of reflecting structures along its length, wherein each structure reflects light at a physical length of at least part of the reflecting structure; characterised in that the reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them.

2. A strain sensor according to Claim 1 in which the reflecting structures which reflect at adjacent wavelengths are configured such that one structure reflects light at one characteristic wavelength and the structure adjacent in wavelength reflects light at two characteristic wavelengths.

3. A strain sensor according to Claim 2 in which the reflecting structure which is selected to reflect light at two characteristic wavelengths.

4. A strain sensor according to any preceding claim in which the optical waveguide comprises an optical fibre.

## CLAIMS

sensor, said light having a wavelength range which covers at least the range of preceding claim, a light source operable to apply light to the waveguide of the apparatus for measuring strain; comprising a sensor according to any

accompanying drawings.

9. A strain sensor substantially as hereinbefore described or substantially as illustrated by way of reference to the Figure 1 of Figure 2 or Figure 3 of the

10. Apparatus for measuring strain; comprising a sensor according to any

doped with germanium oxide.

8. A strain sensor according to Claim 7 in which the optical fibre comprises silica

structure is optically written into the fibre.

7. A strain sensor according to Claim 5 or 6 when dependent on Claim 4 in which the optical fibre includes a photorefractive dopant and the or each gratings

comprises a Bragg grating.

6. A strain sensor according to Claim 5 in which the or each grating structure

grating.

5. A strain sensor according to any preceding claim in which the or each characteristic wavelength is in consequence of a change in the pitch of the reflecting structure comprises a grating structure and wherein the change in reflecting structure is a grating

11. Apparatus for measuring strain according to Claim 10 in which the detector determines the change of characteristic wavelength at which the reflecting structures reflect light, said changes being indicative of a change in length of structures reflecting light, at least a part of the respective reflecting structure.

12. Apparatus for measuring strain according to Claim 10 in which the detector means determines the change in characteristic wavelength by measuring the means measures light transmitted by the sensor and determines the change in characteristic wavelength by measuring the changes in wavelength at which the sensor reflects light.

13. Apparatus according to any one of Claims 10 to 12 in which the detector means further comprises means for utilising the relative magnitude of the means intensity of reflected light or the relative magnitude of the intensity at which transmission is attenuated.

14. An apparatus for measuring strain substantially as hereinbefore described or substantially as illustrated by way of reference to the Figure 1 of the accompanying drawings.

15. A method of measuring strain comprising; providing a sensor according to any one of Claims 1 to 8, applying light to the waveguide of the sensor, said light having a wavelength range which covers at least the range of wavelengths over which the reflecting structure reflects light, and detecting any change in the characteristic wavelength at which the reflecting structures reflect light. 16. A method according to Claim 15 comprising detecting the change in characteristic wavelength by measuring the wavelengths at which the sensor reflects light. 17. A method according to Claim 15 comprising detecting the change in characteristic wavelength by measuring the wavelengths at which the sensor transmits light through the sensor is attenuated. 18. A method according to Claim 16 or Claim 17 and further comprising detecting the relative magnitude of the intensity of reflected light or the relative magnitude of the intensity at which transmitted light is attenuated to discriminate between reflecting structures which are adjacent in wavelength. 19. A method according to any one of Claims 15 to 18 and further comprising sweeping the wavelength of the light applied to the sensor.

20. A method according to any one of Claims 15 to 19 in which, when it is desired to measure strain within an object, further comprises securing a part of the waveguide having at least a part of one of the reflecting structures to the object such that a change in the physical length of at least a part of the reflecting structures causes a change in the physical length of at least a part of the reflecting waveguide having at least a part of one of the reflecting structures to the object to measure the temperature of an object, further comprises placing a part of the waveguide having at least a part of one of the reflecting structures in thermal contact with the object such that a change in the temperature of the object causes a change in the physical length of at least a part of the reflecting waveguide to measure the strain in the object.

21. A method according to any one of Claims 15 to 19 in which, when it is desired to measure the temperature of an object, further comprises placing a part of the waveguide having at least a part of one of the reflecting structures in thermal contact with the object such that a change in the physical length of at least a part of the reflecting waveguide causes a change in the physical length of at least a part of the reflecting structure.

22. A method of strain sensing substantially as hereinbefore described.

Figure 1

A strain sensor comprises an optical waveguide (6) having a plurality of reflecting structures (Bragg gratings) along its length. Each structure reflects light at a different characteristic wavelength ( $\lambda_1$  to  $\lambda_{n+1}$ ) which changes in dependence on a change of physical length of at least part of the reflecting structure. The reflectivity of reflecting structures which reflect at characteristic wavelengths which are adjacent to each other ( $\lambda_1$  and  $\lambda_2$  or  $\lambda_n$  or  $\lambda_{n+1}$ ) are configured to be different such that the intensity of light reflected from adjacent structures can be used to discriminate between them.

## ABSTRACT



Figure 1

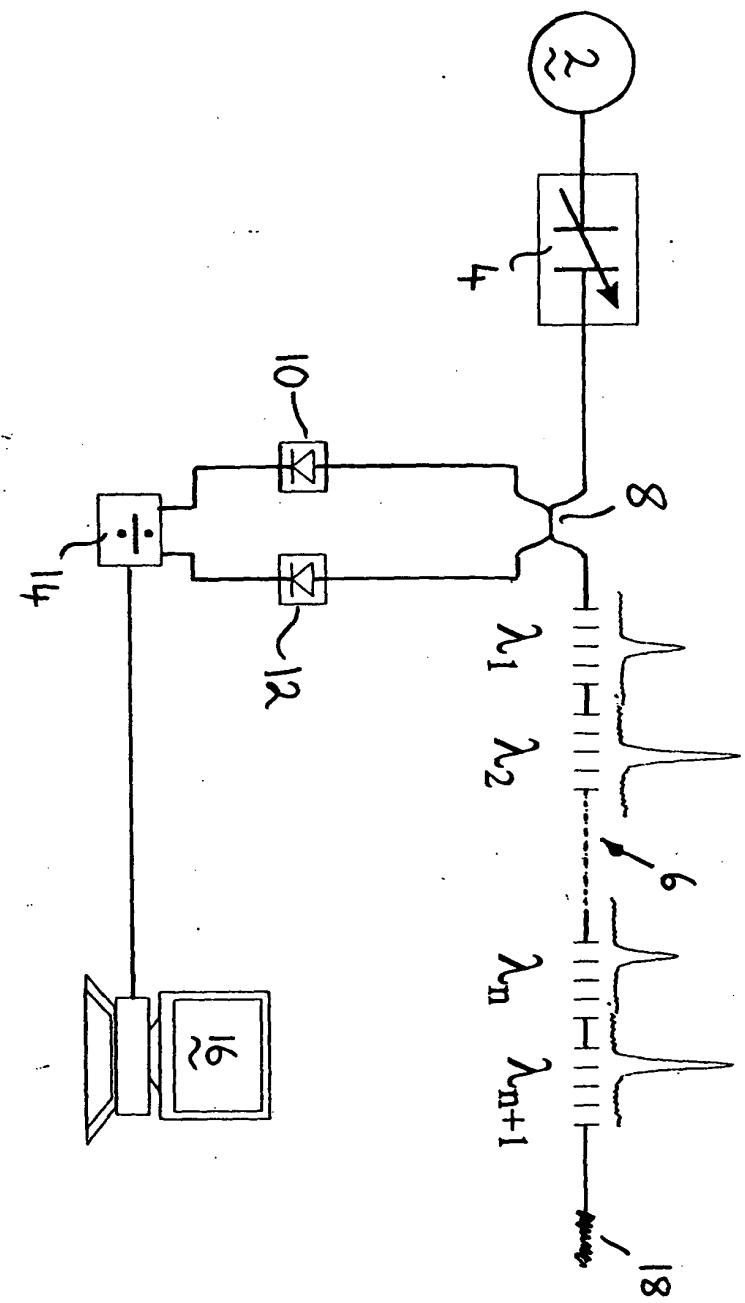




Figure 2 (b)

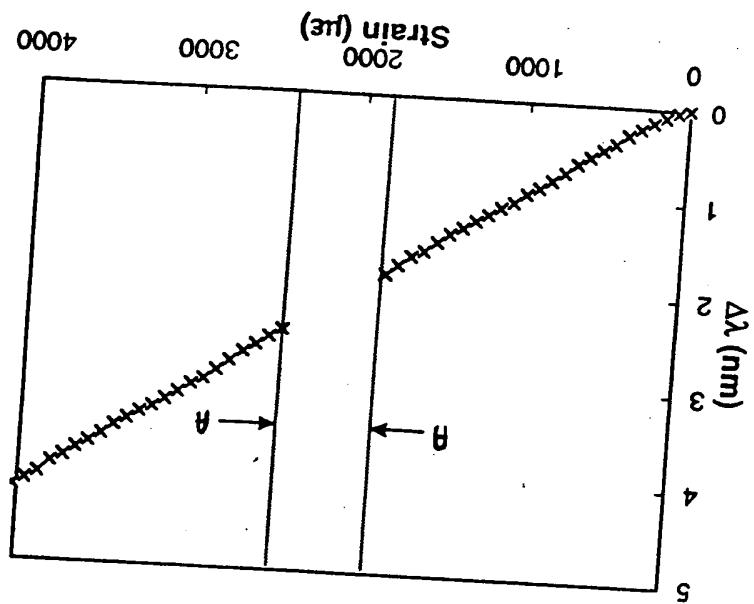
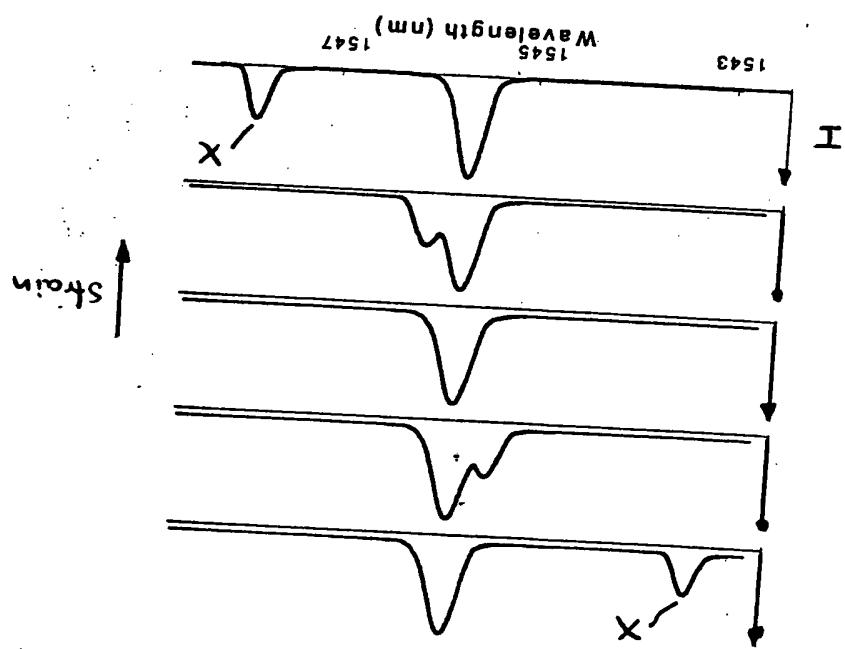


Figure 2 (a)



2/3



Figure 3 (b)

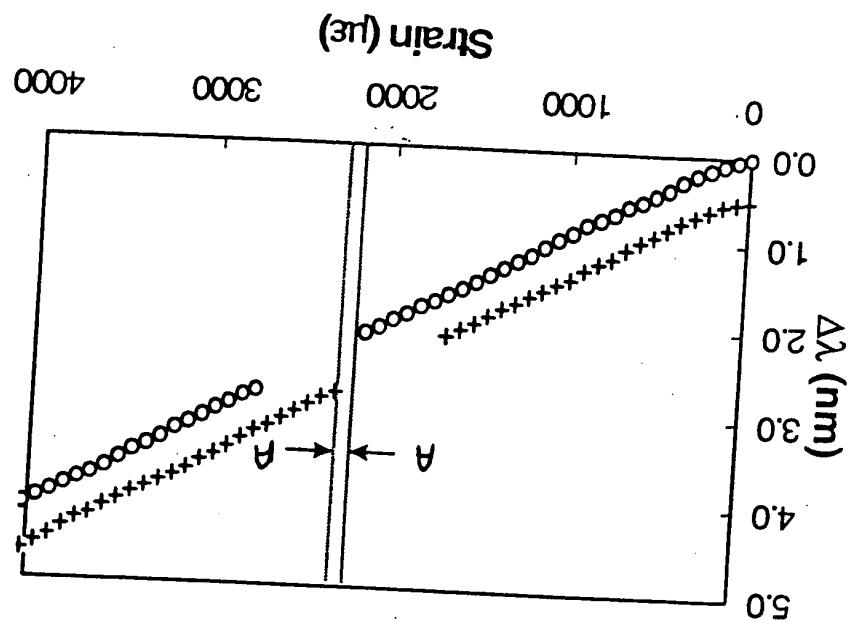
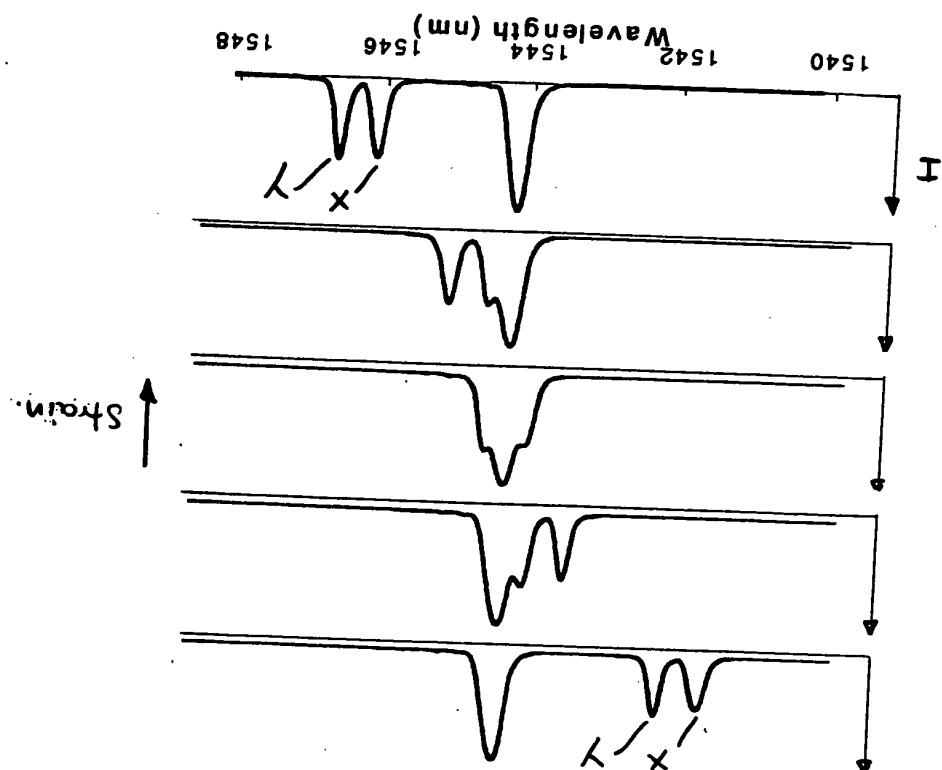


Figure 3 (a)



3/3

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